Thermoelectric System Economics: Where the Laws of Thermoelectrics, Thermodynamics, Heat Transfer, and Economics Intersect

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AGENDA

Motivations

System Cost Modeling & Integration with System-Level Analysis

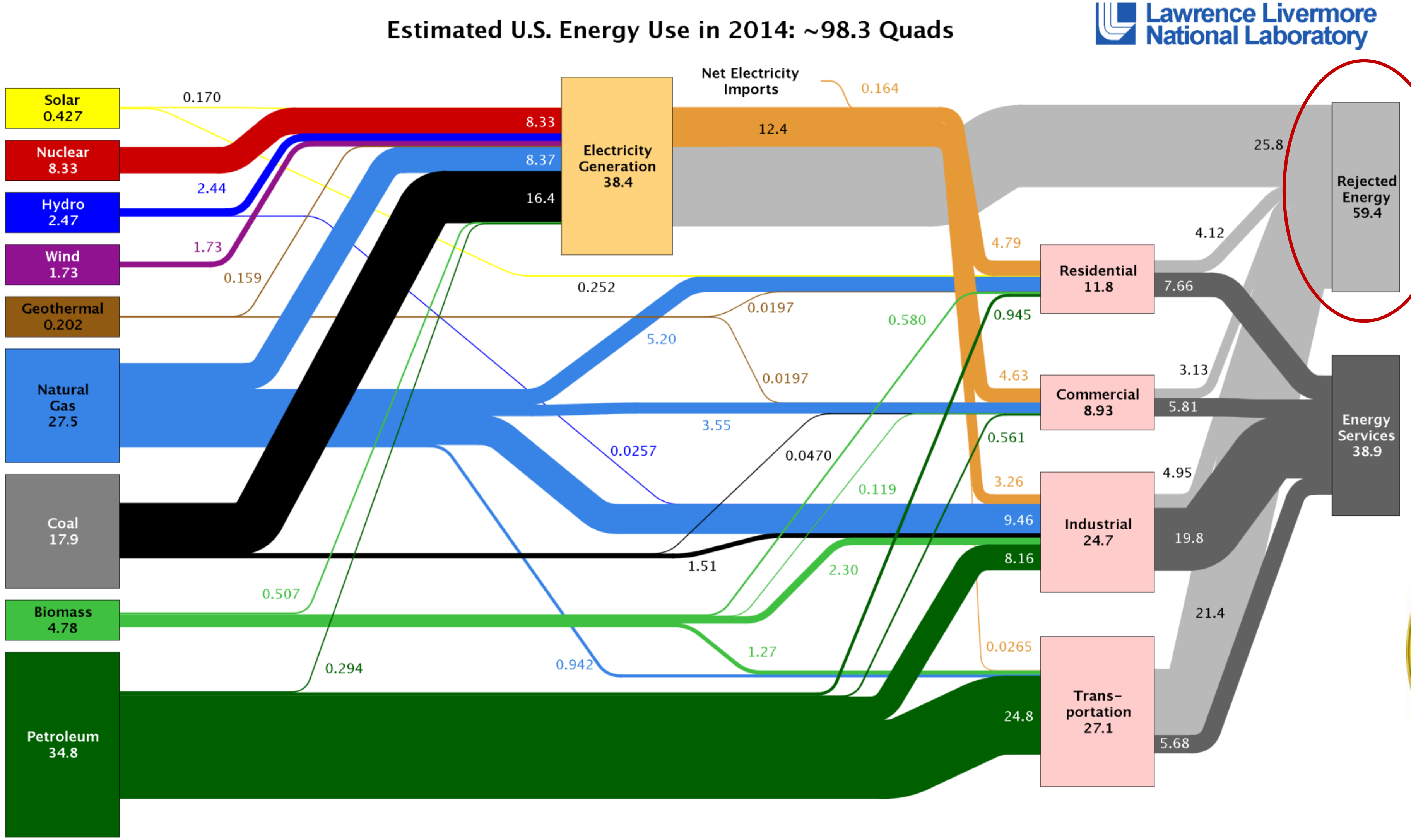
Characteristics of Cost Minimization When HEX Rigorously Included (G_{opt} , F_{opt}) Relationships

Cost Minimization Relationships

Cost Regime Mapping

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

United States Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Waste Heat To Be "Harvested"

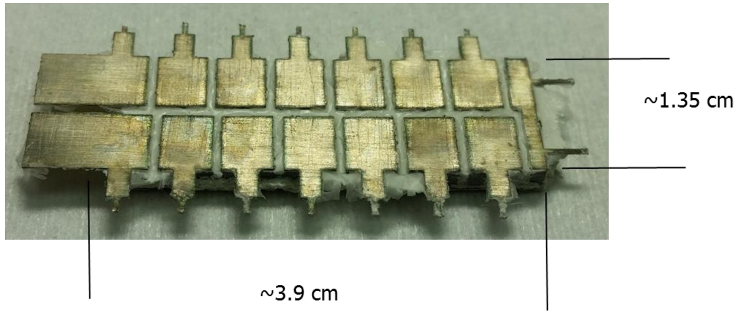
  59.4 Quads

- Up ~ 5 Quads From 2009

Terrestrial Waste Energy Recovery

- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
  - Maximizing Conversion Efficiency
  - Maximum Power Output

High Performance, High Power Flux Skutterudite TE Module Technology

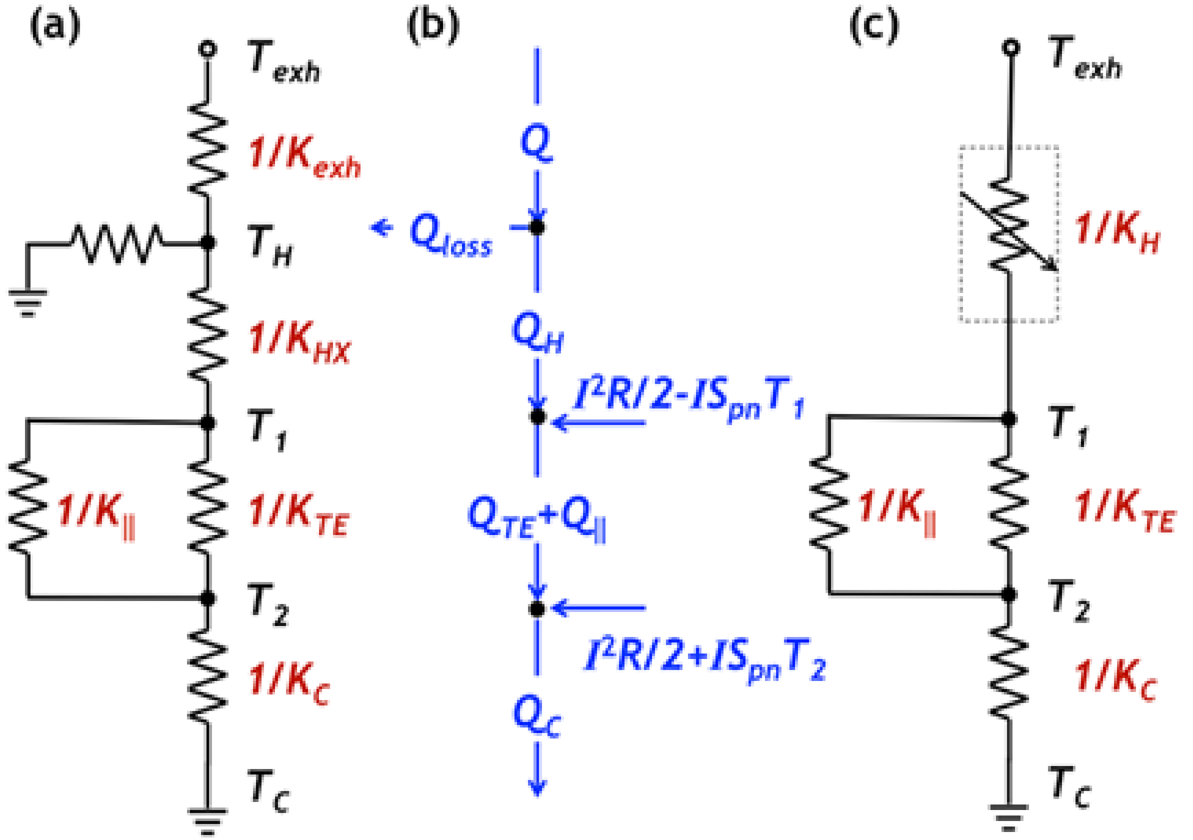


- However, JPL is Currently Working on System Designs Where the Critical Design Metric is Maximizing Specific Power (W/kg)
  - Knowing Its Relationship to Maximum Power or Efficiency Points is Key
  - T_{exh} = 823 K; T_{amb} = 273 K
- In Additional, Key Barriers Are Not So Much Performance Anymore as System-Level Cost (As Discussed in 2015 ICT, Dresden, Germany and ECT 2016, Lisbon)

Cost Modeling and Integrating Cost Modeling With System-Level Performance Modeling is Critical

Energy Recovery Thermal / Thermoelectric Modeling

- General Thermal / Thermoelectric Circuit Used Analysis
  - (a) Thermal resistance network for exhaust heat recovery including leakage from the hot-side heat exchanger.
  - (b) General heat and electrical energy flows.
  - (c) Equivalent (traditional) thermal circuit.



Must Develop Technologies / Methods to Recover Energy Economically

- Leverage Cost Modeling Work of LeBlanc et al. [1] and Yee et al. [2]
- Combine with System-Level Analysis Work of Hendricks et al. [3]
- Include the Effects of Real-World Heat Exchangers in More Rigorous Cost Analysis Methodology
  - Cost & Performance (Heat Exchanger UA_h)
  - Heat Exchanger Interfacial Heat Flux
  - Rigorously Account for Different Operational Areas
- Hendricks et al. [3] Analysis Modified to Add in Fill Factor, F, and Heat Exchanger Area, A_{HEX}, into System Analysis Techniques
- Fill Factor and Heat Exchanger Area Are No Long "Arbitrarily Selected" Design Parameters – Part of Design Optimization Process

$$F = \frac{A_{TE}}{A_{HEX}}$$

$$\left(\frac{V}{N}\right)^{*} = f_v(T_h, T_c)$$

$$\left(I \cdot \frac{L}{F \cdot A_{HEX}}\right)^{*} = f_I(T_h, T_c)$$

$$\eta_{TE}^{*} = \frac{P}{Q_{h,TE}} = f_{eff}(T_h, T_c)$$

$$\left(\frac{Q_{h,TE} \cdot L}{N \cdot F \cdot A_{HEX}}\right)^{*} = f_{qh}(T_h, T_c)$$

$$q_{h,HEX}^{*} = F \cdot q_{h,TE}^{*} = \frac{Q_{h,TE} + Q_{loss}}{A_{HEX}} = f_Q(T_{exh}, T_h, T_c)$$

1. S. LeBlanc, S. K. Yee, M. L. Scullin, C. Dames and K. E. Goodson, *Renewable and Sustainable Energy Reviews*, **32**, 313-327, 2014.
2. S. K. Yee, S. LeBlanc, K. E. Goodson and C. Dames, *Energy & Environmental Science*, **6**, 2561-2571, 2013.
3. Hendricks, T.J. and Crane, D. "Thermoelectric Energy Recovery Systems: Thermal, Thermoelectric and Structural Considerations", **CRC Press Handbook of Thermoelectrics & Its Energy Harvesting: Modules, Systems, and Applications in Energy Harvesting**, Book 2, Section 3, Chapter 22, Taylor and Francis Group, Boca Raton, FL, 2012.

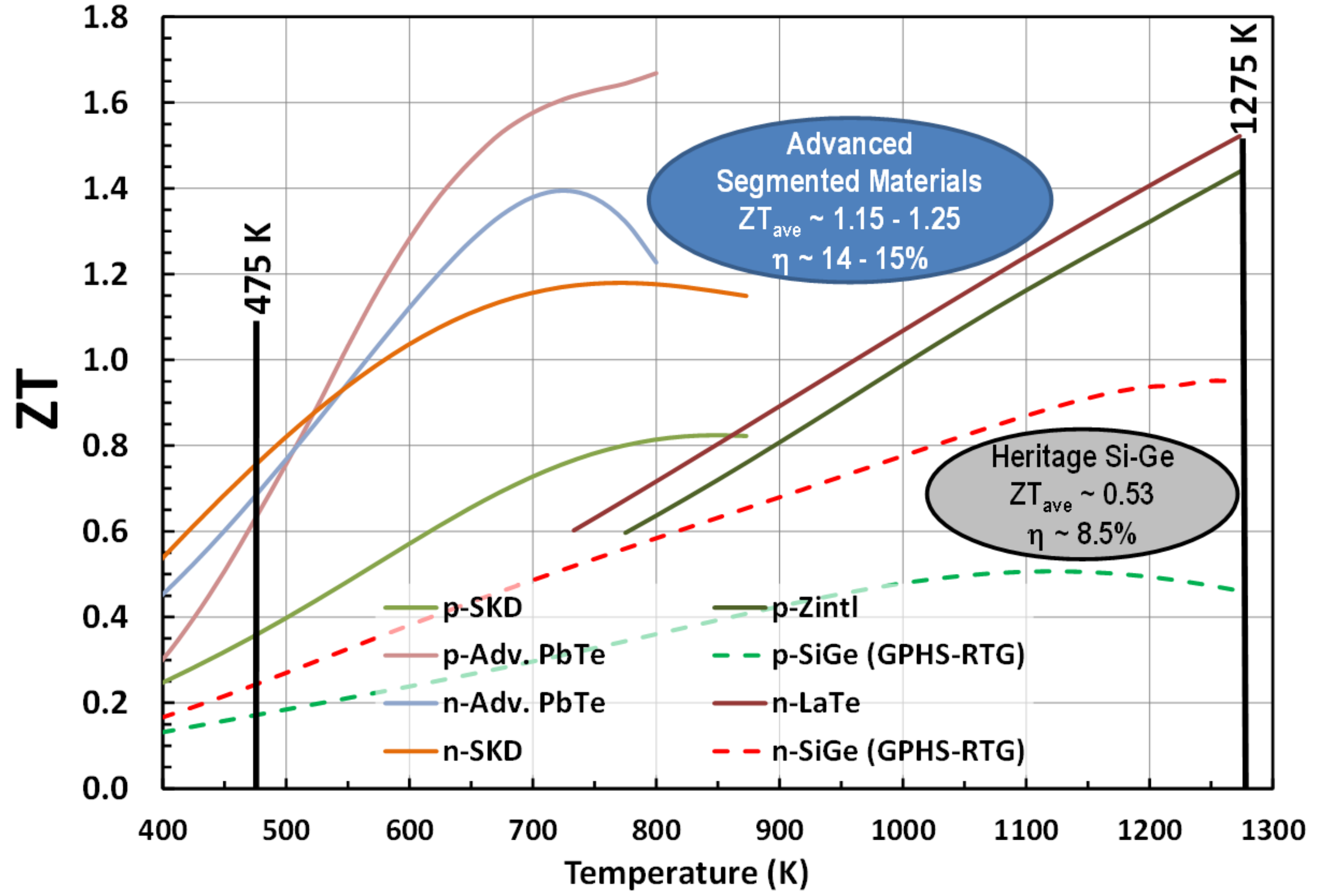
Optimum Cost Fill Factor Analysis

- Optimum Cost Fill Factor of Yee et al.* (2013) Is Different Type of Analysis
  - Did Not Account for Heat Exchanger Heat Flux Conditions
  - Thermal Matching of the Hot-Side and Cold-Side Heat Exchangers
  - $A_u = A_{HEX}$
  - $K_H = UA_{HEX}$
- In Reality TE Module Optimum Fill Factor, F_{opt} , Impacted by:
  - Heat Exchanger Interfacial Heat Flux, $q''_{h,HEX}$
  - Heat Exchanger Effectiveness, UA_h
  - Parasitic Thermal Losses, σ

*Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.

TE Materials Investigated

- Focused on JPL Skutterudites Shown Here In This Initial Work
- Currently Developing and Commercializing These Materials
- We Used JPL Raw Cost Data in This Work



Cost Modeling Approach

- Costs-per-Watt Relationships Become More Complex When Heat Exchanger Performance, UA_h, Heat Exchanger Heat Flux, $q''_{h,HEX}$, and Different System Areas Accounted For
  - A_{TE}, A_{HEX} , and A_u Are Considered in Rigorous Detail; A_{HEX} and A_u Can Be Very Different in Magnitude
- Yee et al. [1] and LeBlanc et al. [2] Have Shown that Heat Exchanger Costs Can Be Characterized by $C_{HEX,H}$ & $C_{HEX,C}$
  - \$/(W/K) – Basically Cost per UA of the Heat Exchangers
  - Here We Include the Hot-Side and Cold-Side Heat Exchangers Individually
- Started Over With Fundamental Cost and G Relationships of Yee et al.
  - Did NOT Invoke Simplifying Assumptions of Yee et al.

[1] Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.
[2] LeBlanc, S., Yee, S. K., Scullin, M. L., Dames, C., and Goodson, K. E., *Renewable and Sustainable Energy Reviews, 2014,* **32**, 313-327.

$$C_{TEG}[\$] = \left(C''' \cdot L + C''\right) \cdot F \cdot A_{HEX} + \left(C_{HEX,h} \cdot K_H + C_{HEX,c} \cdot K_C\right)$$

$$G\,[\$/W] = \frac{\text{Total TEG Costs}}{P} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot Q_H} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot (1-\sigma) Q}$$

$$G = \frac{4 \cdot (m+1)^2}{S_{pn}^{\ 2} \cdot \sigma \cdot m \cdot (T_{exh} - T_{amb})^2} \cdot \left[\frac{1.1 \cdot \kappa_{TE} \cdot A_{HEX} \cdot F}{K_H} + L\right]^2 \cdot \left[C''' + \frac{C''}{L} + \frac{C_{HEX} \cdot UA_u}{A_{HEX} \cdot L \cdot F}\right]$$

$K_C / K_H > 10$ to 20 Incorporated this Added Relationship for Maximum Power**

T. J. Hendricks, "Integrated Thermoelectric–Thermal System Resistance Optimization to Maximize Power Output in Thermoelectric Energy Recovery Systems, Mater. Res. Soc. Symp. Proceedings, **1642, Materials Research Society, mrsf13-1642-bb02-04 doi:10.1557/opl.2014.443, 2014.

Optimum Cost Function

- G_{opt} (F_{opt}, κ_{TE}, K_H, L_{TE}, A_{HEX}, Cost Parameters) is a complex function of 5 design parameter groups:
  - [κ_{TE} L_{TE} / K_H] - Non-dimensional – Tied to TE Device/Heat Exchanger interfacial design parameters
  - [F_{opt} A_{HEX} / L_{TE}^2] – Non – Dimensional – TE device design parameters
  - [C_{HEX} UA_U] / [C''' L_{TE}^3 + C'' L_{TE}^2] - Non-dimensional - Ratio of heat exchanger costs to TE device costs
  - [κ_{TE} A_{HEX} / (K_H L_{TE})] – Non-dimensional - Tied directly to interfacial heat flux
  - $1/[(S\Delta T)^2 \cdot \sigma \cdot L_{TE}]$ – Power factor effect
- At least two separate and distinct design areas involved (A_U & A_{HEX}) - Must treat them separately as they are NOT even nearly equal
- G_{opt} is a function of the TE/heat exchanger interfacial heat flux and UA_U – One cannot escape this fact
- Relationship below shows the comprehensive relationship that ties costs to heat exchanger design parameters

$$\frac{G_{opt}\left(\frac{\$}{W}\right)\cdot(S\cdot\Delta T)^2\cdot\sigma\cdot L_{TE}\cdot m}{4\cdot(C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2)\cdot(m+1)^2}=\left(\frac{1.1\cdot\kappa_{TE}\cdot A_{HEX}\cdot F_{opt}}{K_H\cdot L_{TE}}+1\right)^2\cdot\left[1+\left(\frac{(C_{HEX,H}+C_{HEX,C})\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L_{TE}^2}{A_{HEX}\cdot F_{opt}}\right)\right]$$

Note: $\Delta T = T_{exhaust} - T_{ambient}$

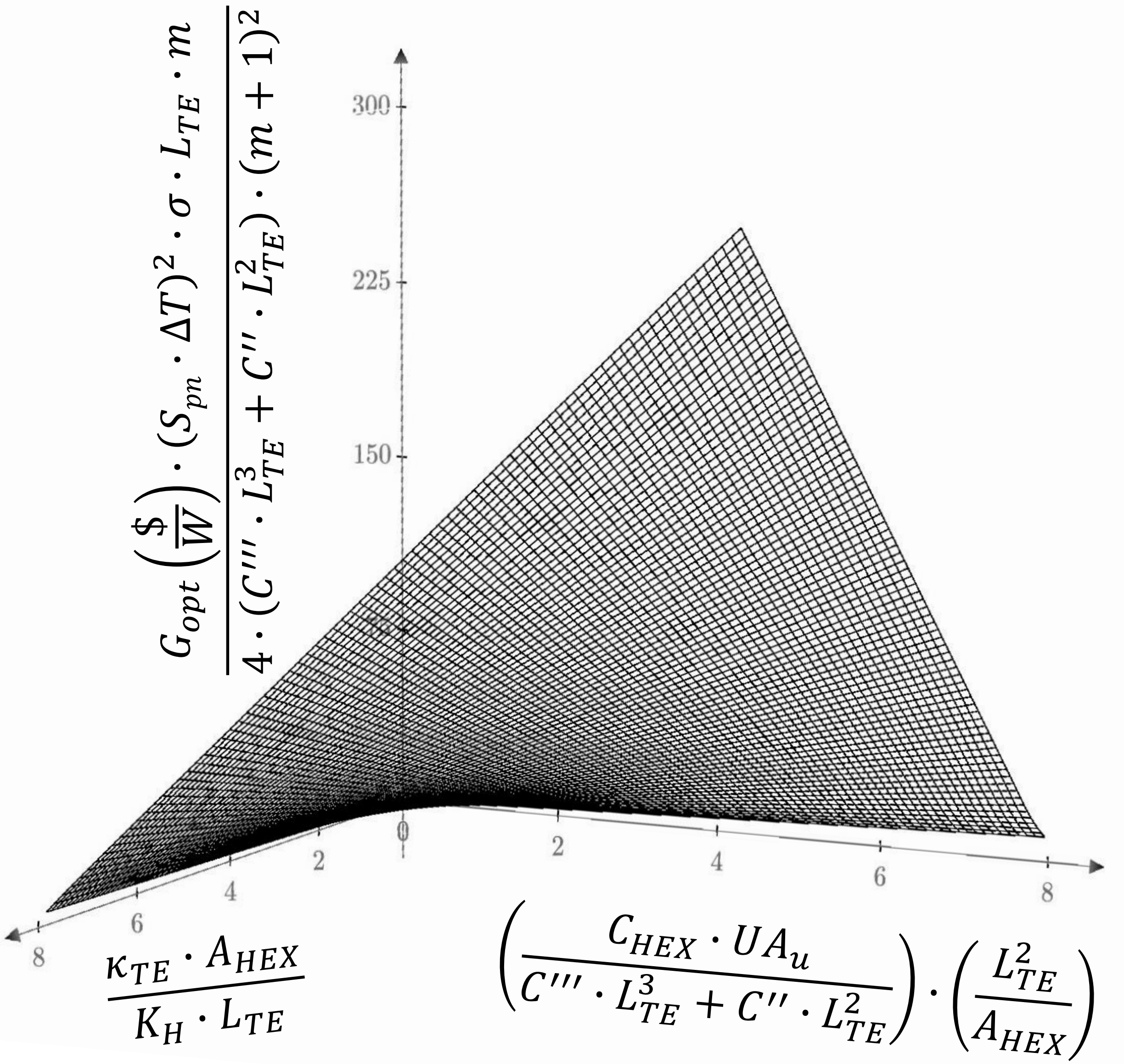
Coupled DIRECTLY to Interfacial Heat Flux

$$F_{opt}=\left(-\tfrac{1}{4}\left(\frac{(C_{HEX,H}+C_{HEX,C})\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L_{TE}^2}{A_{HEX}}\right)+\tfrac{1}{4}\sqrt{\left(\frac{(C_{HEX,H}+C_{HEX,C})\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)^2\cdot\left(\frac{L_{TE}^2}{A_{HEX}}\right)^2+\frac{8}{1.1}\cdot\left(\frac{L_{TE}^2}{A_{HEX}}\right)\cdot\left(\frac{K_H\cdot L_{TE}}{\kappa_{TE}\cdot A_{HEX}}\right)\left[\frac{(C_{HEX,H}+C_{HEX,C})\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right]}\right)$$

Non-Dimensional TEG Costs Visually

- No real minimums or optimums – Non-dimensional cost simply increasing with two non-dimensional parameters shown
- Non-dimensional cost decreases as hot-side heat flux increases
- TE converter design parameters embedded
  - Dependence on L_{TE} is quite complex and nc immediately obvious

$$F_{opt} = \text{function}\left[\left(\frac{\kappa_{TE}\cdot A_{HEX}}{K_H\cdot L_{TE}}\right), \left(\frac{C_{HEX}\cdot UA_u}{C'''\cdot L_{TE}^3 + C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L}{A}\right.\right.$$



Critical Low TEG Cost Relationships

- Two Critical Cost-Determining Factors:

$$\frac{1.1\cdot\kappa_{TE}\cdot A_{HEX}\cdot F_{opt}}{K_H\cdot L_{TE}}<0.05 \qquad \left(\frac{C_{HEX}\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L_{TE}^2}{A_{HEX}\cdot F_{opt}}\right)<0.05$$

- Which we generally want to minimize (At least we would like to) – But can one do this?
- First criteria generally states that we want increased heat fluxes

$$\frac{22\cdot\kappa_{TE}\cdot(T_{exh}-T_{hot})\cdot F_{opt}}{L_{TE}}<q''_{h,HEX}$$

- But this actually creates a competition/conflict with interfacial energy equation, one cannot actually satisfy this relation – too severe, so there is a limit here
  - Goal would be achieve as high a heat flux as possible consistent with interfacial energy equation

$$\frac{2.2\cdot\kappa_{TE}\cdot(T_{exh}-T_{hot})}{L_{TE}}\left[\frac{1}{\left(\frac{C_{HEX}\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L_{TE}^2}{A_{HEX}}\right)}+0.5\right]>q''_{h,HEX}$$

- Second criteria generally states that we want low-cost heat exchange systems
- Establishes relationships between TE converter design parameters and cost parameters for low-cost

Critical Low TEG Cost Relationships

- (G_{opt}, F_{opt}) Relations Now Give Us a Window into Two Critical Cost Minimization Relationships

$$\left(\frac{(C_{HEX,h} + C_{HEX,c}) \cdot UA_u}{C''' \cdot L_{TE}^3 + C'' \cdot L_{TE}^2}\right) \cdot \left(\frac{L_{TE}^2}{A_{HEX} \cdot F_{opt}}\right) < 0.05 \qquad (19)$$

$$\left(\frac{1.1 \cdot \kappa_{TE} \cdot A_{HEX} \cdot F_{opt}}{K_H \cdot L_{TE}}\right) < 0.05 \qquad (20)$$

This is basically ~ Hot-Side Heat Flux, q''_{HEX}

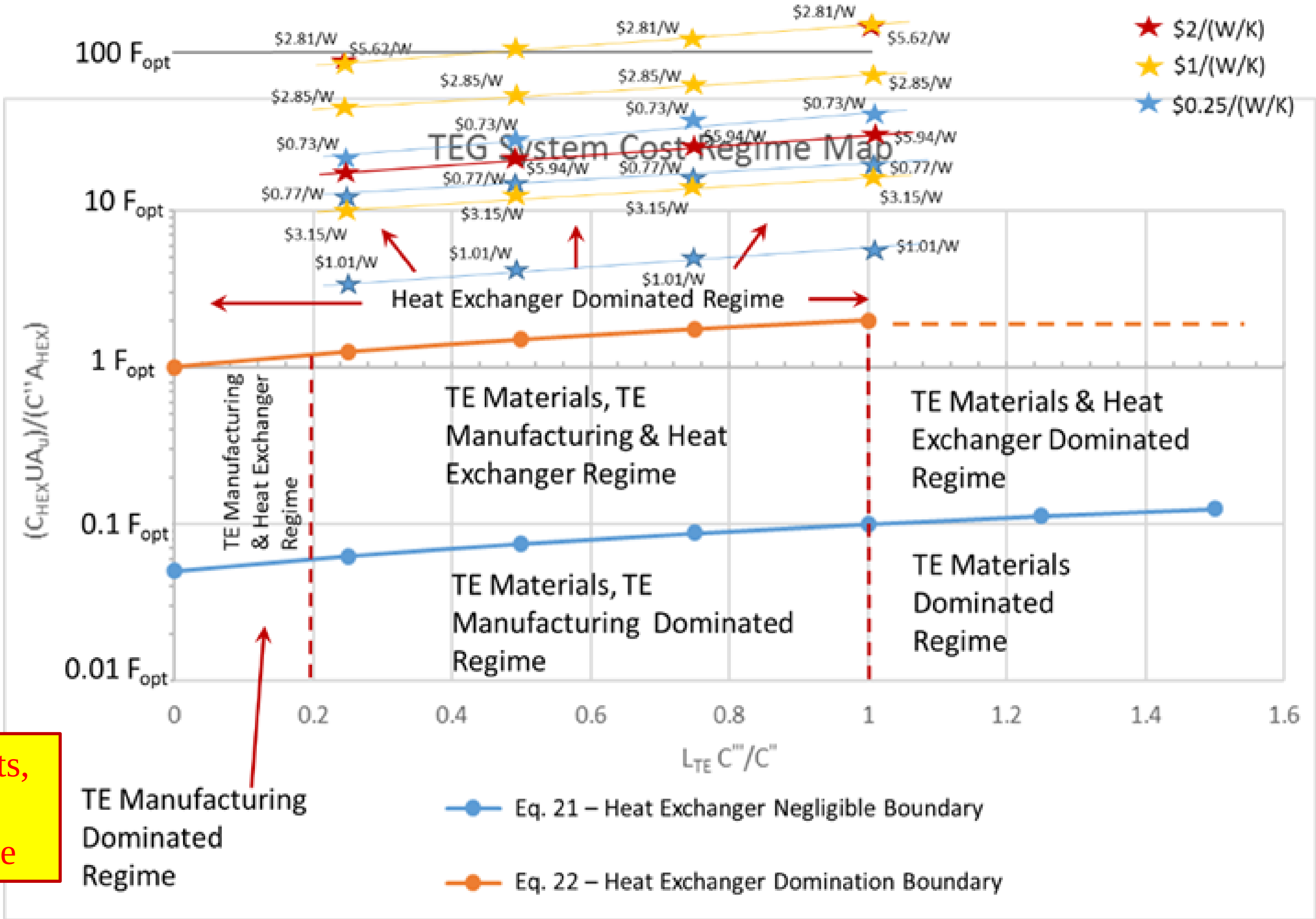
- These Can Be Further Re-Arranged in to Highly Useful Forms that Provide Key Insights On How Heat Exchanger and Thermoelectric Parameters Interact In Minimizing Cost

$$\left(\frac{(C_{HEX,h} + C_{HEX,c}) \cdot UA_u}{C'' \cdot A_{HEX}}\right) < 0.05 \cdot \left(\frac{C''' \cdot L_{TE}}{C''} + 1\right) \cdot F_{opt} \qquad (21)$$

$$\left(\frac{(C_{HEX,h} + C_{HEX,c}) \cdot UA_u}{C'' \cdot A_{HEX}}\right) > \left(\frac{C''' \cdot L_{TE}}{C''} + 1\right) \cdot F_{opt} \qquad (22)$$

Cost Regime Mapping

- Cost Regime Maps Can Now Be Constructed and Explored
- Constant Cost [$/W] Lines are Shown
  - Generally Parallel Lines
  - Closely Parallel to Heat Exchanger Domination Boundaries
- ($1/W) Extremely Challenging
  - Heat Exchangers Must be Very Inexpensive
- ($3/W) More Achievable



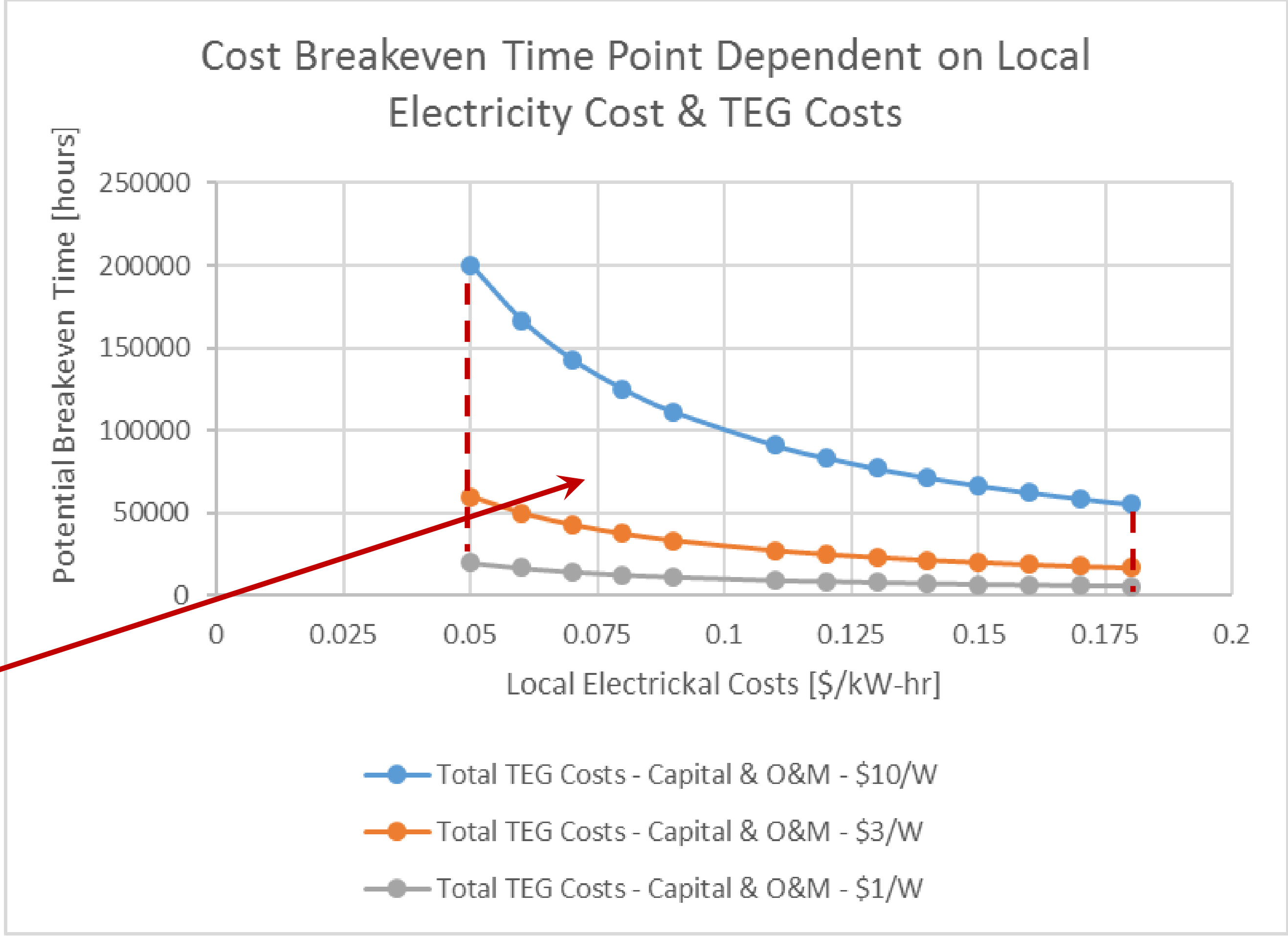
Heat Exchangers Can Dominate The Costs, Even at Low Cost Levels and It is Extremely Difficult to Escape this Regime

TEG Breakeven Point as a Function of Local Electricity Costs

- TEG does add value as it generates useful electrical energy
- Does have an economic benefit depending on local cost of electricity for given application – time dependent

$$t_{BE,Min} \geq \frac{G_{opt} + G_{O\&M}}{Cost_{Electric}}$$

- Simple analysis – No time value of money included
- Does show the point why $1/W is so important
- Applications with longer power production times are key – Play to TEG reliability strengths



Potential Cost Breakeven Envelope

Final Thoughts & Conclusions

- Investigated and Characterized Maximum Specific Power Regimes, Relationships with Maximum Efficiency, Maximum Power, and Low Cost per Watt Regions - Highly Relevant Terrestrial Power System Application
- Leveraged Cost Modeling Methodology of Yee and LeBlanc Combined with TE System-Level Analyses of Hendricks to Develop More Comprehensive Optimum Cost Fill Factor Analysis
  - Fill Factor, F, and Heat Exchanger Mounting Area, A_{HEX}, No Longer Arbitrarily Selected – They are Part of the Optimization
- Hot-Side and Cold-Side Heat Exchanger Performance and Costs More Rigorously & Directly Included
  - Heat Exchanger UA
  - Heat Exchanger Heat Flux
  - All Relevant Areas (A_{TE}, A_{HEX}, and A_u) Accounted For Separately

Expanding Our Energy Toolbox

- New G_{opt} (F_{opt}) Relationship Developed – More Comprehensive Relationship that More Accurately Accounts for UA and $q''_{h,HEX}$ Effects – New Relationship Allows Us to Investigate Cost-Performance Impacts of Various Heat Exchanger Technologies
- G_{opt} and F_{opt} Inextricably Governed by Heat Exchanger Design Parameters and Heat Flux $q''_{h,HEX}$
- Rigorous Cost Regime Mapping Now Possible Showing TE Parameter & Heat Exchanger Parameter Relationships for Cost-Effective, Cost-Competitive TE Systems

New Cost Minimization Criteria Identified & Impacts Elucidated

- Goal is to Transition Terrestrial Power Advances Back into NASA Missions & Systems

Terrestrial Power Advances ⟷ NASA Mission Requirements

ACKNOWLEDGMENTS

This work was carried out under NASA Prime contract NNN12AA01C, at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

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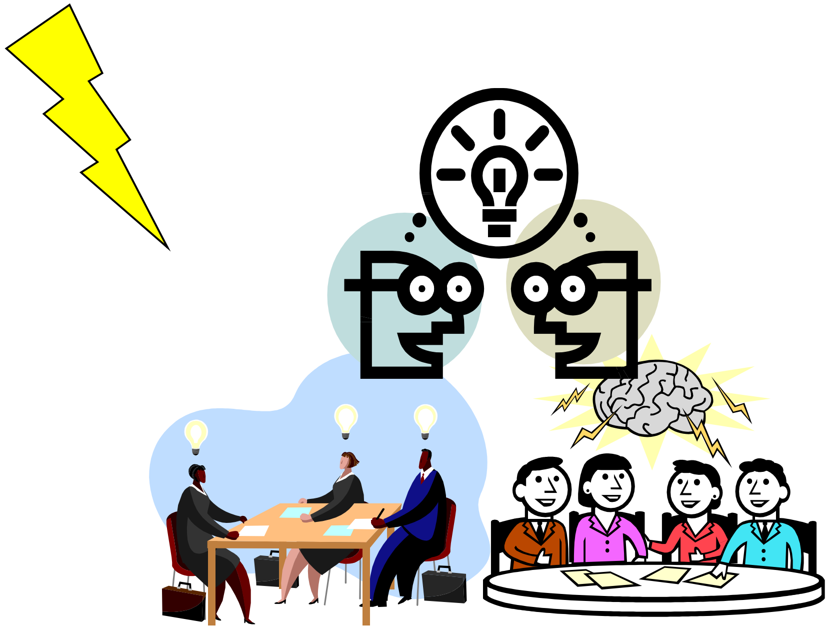
Thank you for your interest and attention

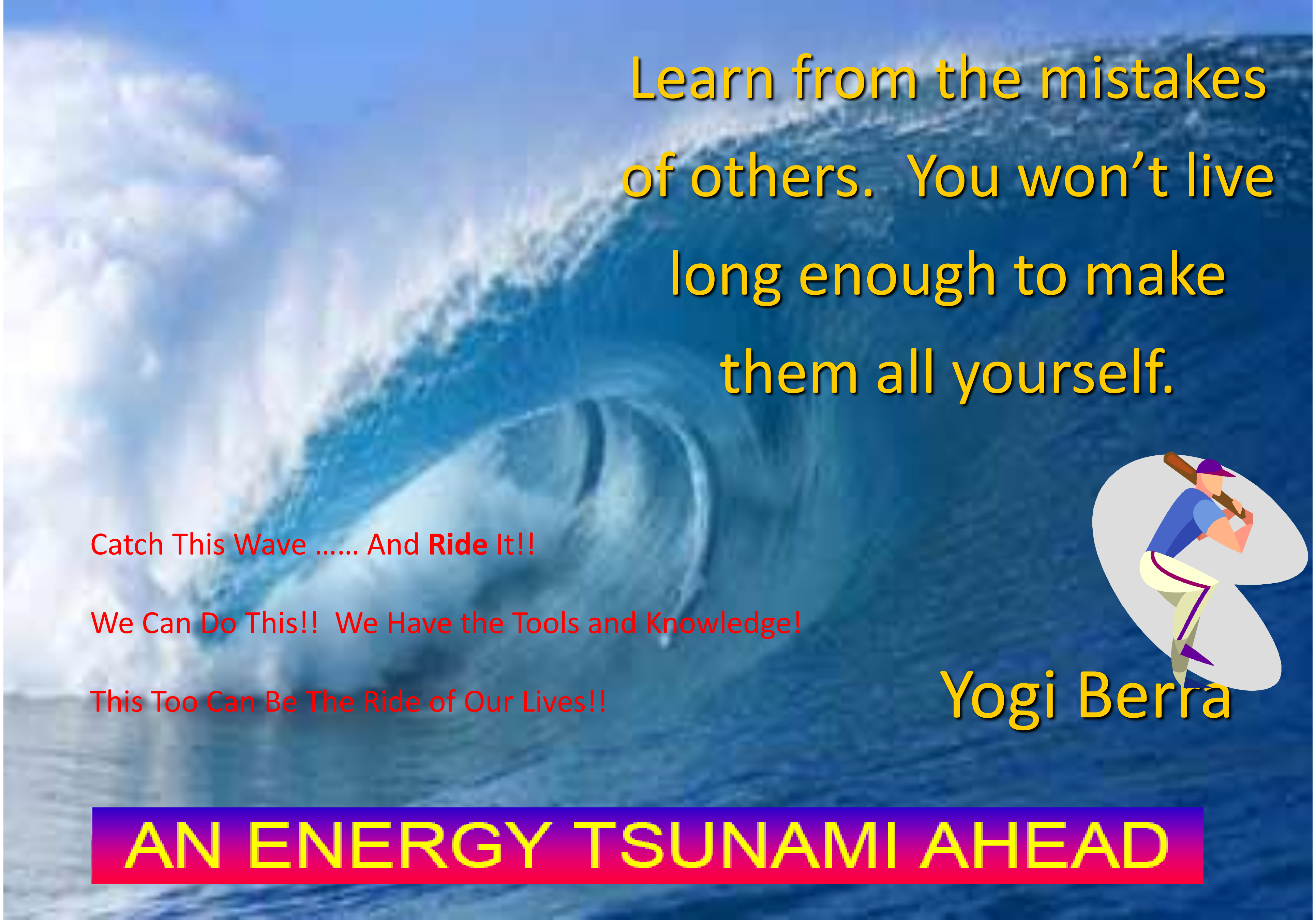
We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

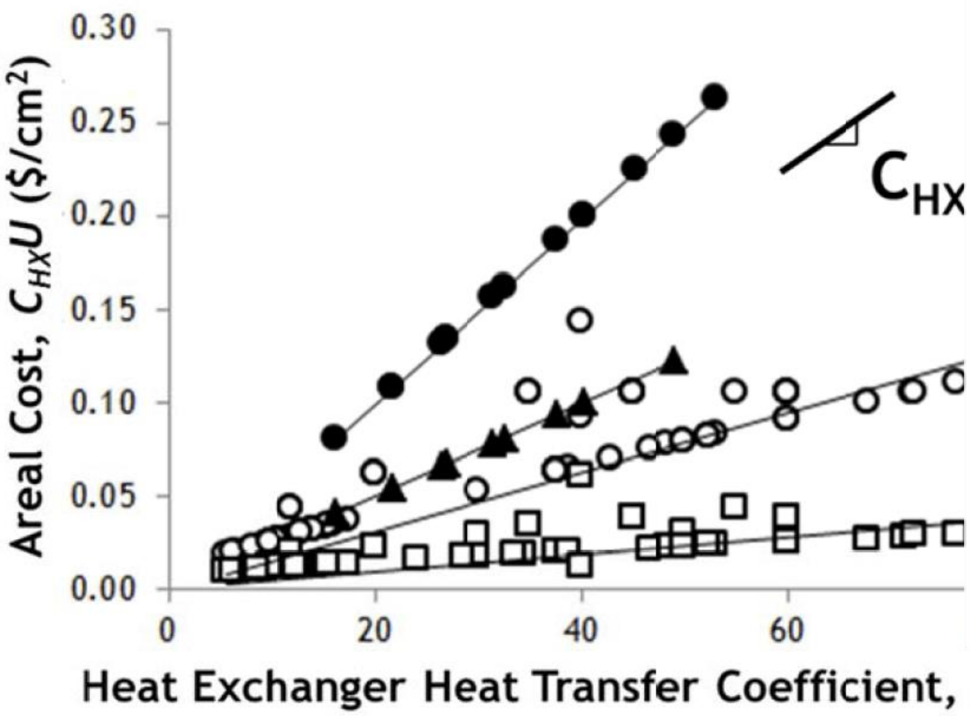
Questions & Discussion



BACKUP


Learn from the mistakes of others. You won't live long enough to make them all yourself.
Yogi Berra
Catch This Wave …… And **Ride** It!!
We Can Do This!! We Have the Tools and Knowledge!
This Too Can Be The Ride of Our Lives!!
AN ENERGY TSUNAMI AHEAD

Heat Exchanger Cost Characterization



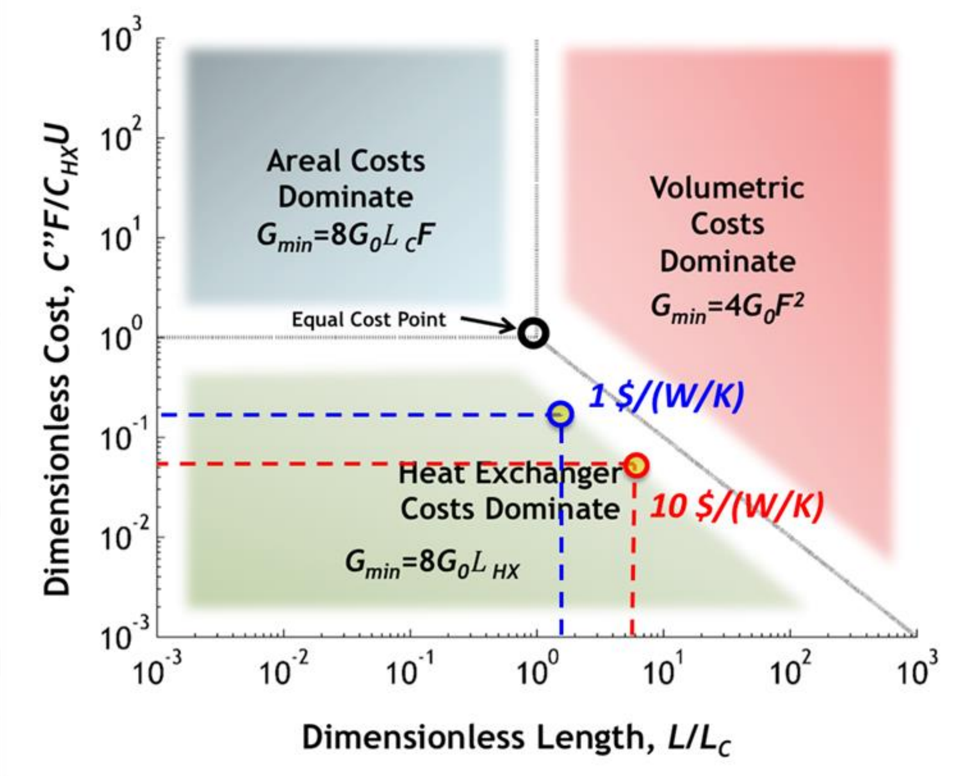


Figure S1: Heat exchanger costs. Typical areal cost as a function of heat transfer coefficient for tube and shell (open points) and plate and fin heat exchangers (solid points). The cost depends on the heat flow Q_H and temperature difference (T_H-T_1). For K_H= Q_H/(T_H-T_1)= 5 kW/K (circles), 10 kW/K (triangles), and 30 kW/K (squares). Data extracted from Ref. 17.

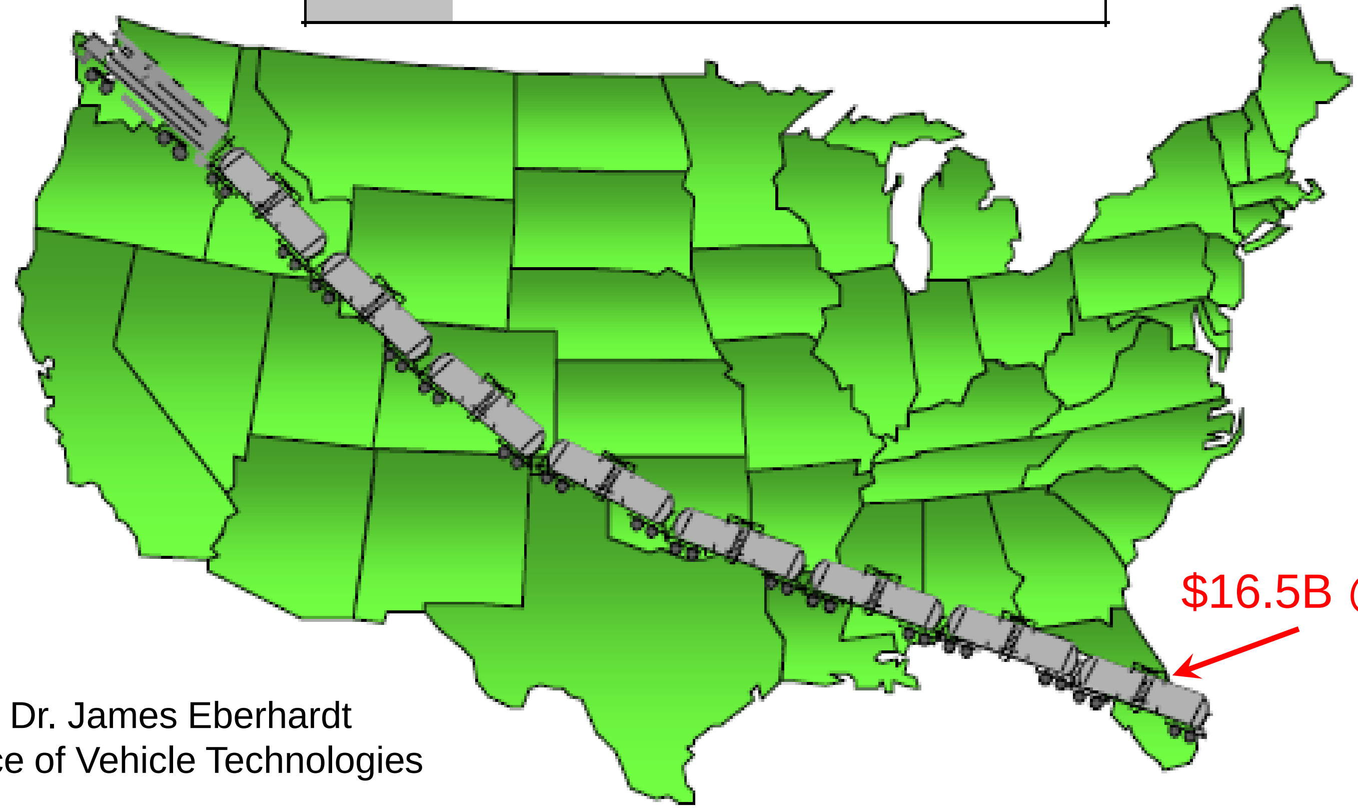
The Magnitude of Our Energy Problem

Office of Heavy Vehicle Technologies

	1973	1997
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

2014
~98.3 Quads[1]

[1]U.S. Energy Information Agency



$16.5B @ $50/Barrel

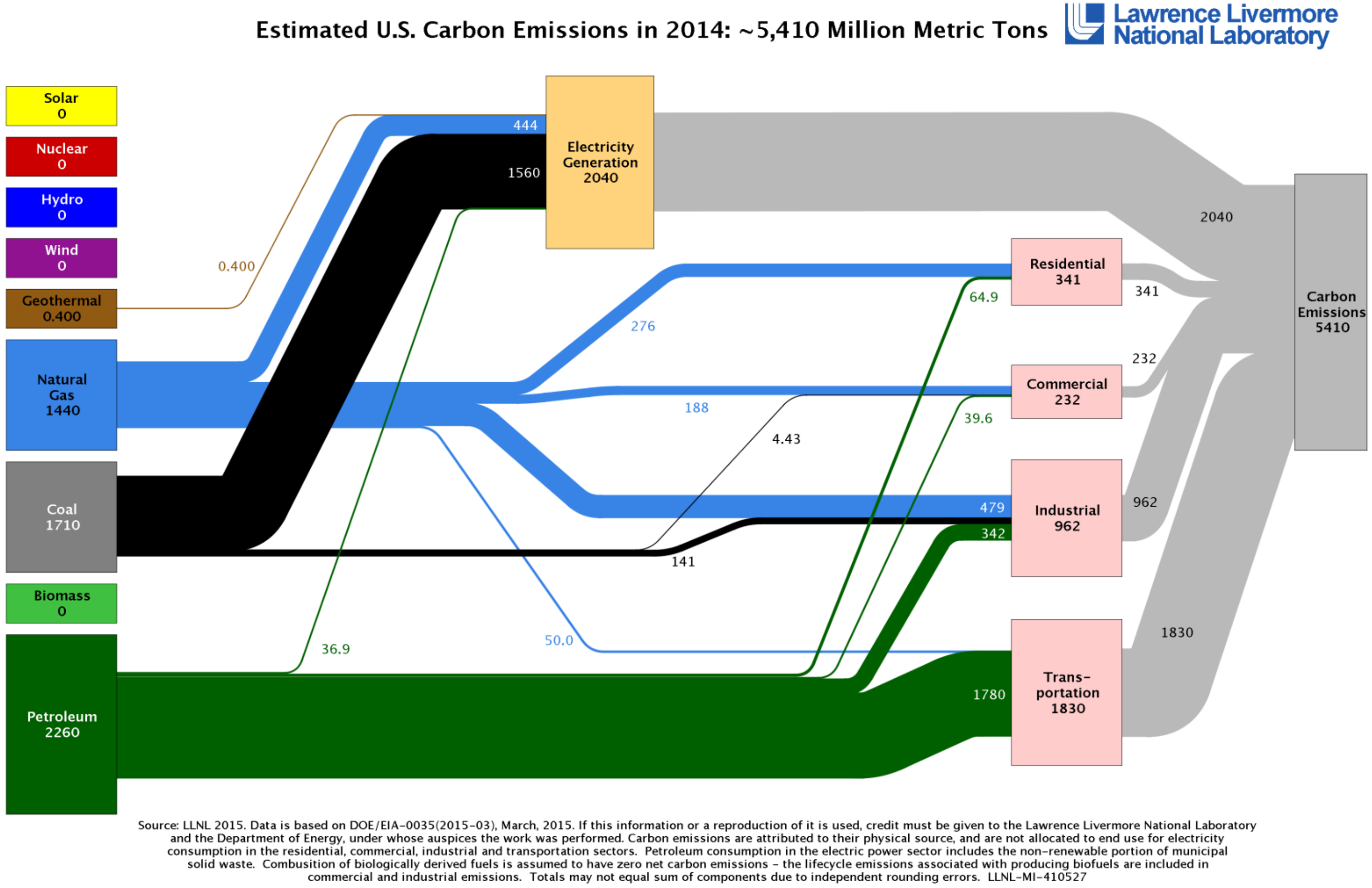
Reference - Dr. James Eberhardt
DOE – Office of Vehicle Technologies

1 Quad of energy is equivalent to 340,000 tank cars of crude oil stretched from Miami to Seattle (3,300 miles).

Environmental Effects Are Strongly Tied to Our Energy Use

- ~1 kg of CO_2 produced per 1 kWhr   (Coal Produced Power)
- ~0.5 kg of CO_2 is produced for 1 kWhr (Natural Gas Power)
- Coal Price $52.45 / short ton (28 April) = ~2.62 / Million BTU
- Natural Gas Spot Price $2.5-3.25/Million BTU (U.S. Spot Prices)
  - Has been less than this fairly recently

Down ~400 Million Metric Tons From 2008
Mostly from Reduced Coal & Petroleum Use



TE & Heat Exchanger Costs

	C''' (\$/m³)	C'' (\$/m²)	HEX Costs (\$/(W/K))	$\left(\frac{\kappa_{TE} \cdot A_{HEX}}{K_H \cdot L_{TE}}\right)$	$\left(\frac{C_{HEX} \cdot UA_u}{C''' \cdot L_{TE}^3 + C'' \cdot L_{TE}^2}\right) \cdot \left(\frac{L_{TE}^2}{A_{HEX}}\right)$	$\frac{G_{opt}\left(\frac{\$}{W}\right) \cdot (S \cdot \Delta T)^2 \cdot \sigma \cdot L_{TE} \cdot m}{4 \cdot (C''' \cdot L_{TE}^3 + C'' \cdot L_{TE}^2) \cdot (m+1)^2}$	G (\$/W)	Lte* C'''/C''
Case 1	8.657x10^4	168.3	\$0.5/(W/K)	1.30	22.43	131.9	1.43	1.02
Case 2	8.657x10^4	168.3	\$1/(W/K)	1.30	44.85	259.9	2.81	1.02
Case 3	8.657x10^4	168.3	\$2/(W/K)	1.30	89.7	515.9	5.58	1.02
Case 4	2x8.657x10^4	2x168.3	\$0.5/(W/K)	1.30	11.2	67.8	1.47	1.02
Case 5	2x8.657x10^4	2x168.3	\$1.0/(W/K)	1.30	22.43	131.9	2.85	1.02
Case 6	2x8.657x10^4	2x168.3	\$2.0/(W/K)	1.30	44.85	259.9	5.62	1.02
Case 7	10x8.657x10^4	10x168.3	\$0.5/(W/K)	1.30	2.24	16.1	1.74	1.02
Case 8	10x8.657x10^4	10x168.3	\$1.0/(W/K)	1.30	4.49	29.2	3.15	1.02
Case 9	10x8.657x10^4	10x168.3	\$2.0/(W/K)	1.30	8.97	54.9	5.94	1.02

- The \$1-2/(W/K) Condition Still Does Not Escape the Heat Exchanger Cost-Dominated Regime
- Heat Exchanger dominated region identified

Hendricks, T.J., Yee, S., LeBlanc, S., "Cost Scaling of a Real-World Exhaust Waste Heat Recovery Thermoelectric Generator: A Deeper Dive," *Journal of Electronic Materials*, **45**, Issue 3, 1751-1761, DOI 10.1007/s11664-015-4201-y, Springer, New York, 2015.

TE / Heat Exchanger Interfacial Heat Flux Requirements

	C''' ($/m^3)	C'' ($/m^2)	HEX Costs ($/(W/K))	$\left(\frac{\kappa_{TE} \cdot A_{HEX}}{K_H \cdot L_{TE}}\right)$	$\left(\frac{C_{HEX} \cdot UA_u}{C''' \cdot L_{TE}^3 + C'' \cdot L_{TE}^2}\right) \cdot \left(\frac{L_{TE}^2}{A_{HEX}}\right)$	q_{low} (W/cm^2) Eq. 20	q_{high} (W/cm^2) Eq. 19
Case 1	8.657x10^4	168.3	$0.5/(W/K)	1.30	22.43	213.6	17.58
Case 2	8.657x10^4	168.3	$1/(W/K)	1.30	44.85	219.5	16.86
Case 3	8.657x10^4	168.3	$2/(W/K)	1.30	89.7	222.7	16.5
Case 4	2x8.657x10^4	2x168.3	$0.5/(W/K)	1.30	11.2	203.3	19.0
Case 5	2x8.657x10^4	2x168.3	$1.0/(W/K)	1.30	22.43	213.6	17.58
Case 6	2x8.657x10^4	2x168.3	$2.0/(W/K)	1.30	44.85	219.5	16.86
Case 7	10x8.657x10^4	10x168.3	$0.5/(W/K)	1.30	2.24	157.6	30.53
Case 8	10x8.657x10^4	10x168.3	$1.0/(W/K)	1.30	4.49	180.9	23.33
Case 9	10x8.657x10^4	10x168.3	$2.0/(W/K)	1.30	8.97	198.9	19.7

- The $1-2/(W/K) Condition Still Does Not Escape the Heat Exchanger Cost-Dominated Regime
- Heat Exchanger dominated region identified

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TE & Heat Exchanger Cost Regimes

	C''' ($/m³)	C'' ($/m²)	HEX Costs ($/(W/K))	$\left(\frac{\kappa_{TE}\cdot A_{HEX}}{K_H\cdot L_{TE}}\right)$	$\left(\frac{C_{HEX}\cdot UA_u}{C''\cdot A_{HEX}}\right)$	$\frac{L_{TE}\cdot C'''}{C''}$
Case 1	$8.657\text{x}10^4$	168.3	$0.5/(W/K)	1.30	45.5	1.02
Case 2	$8.657\text{x}10^4$	168.3	$1/(W/K)	1.30	91.05	1.02
Case 3	$8.657\text{x}10^4$	168.3	$2/(W/K)	1.30	182.1	1.02
Case 4	$2\text{x}8.657\text{x}10^4$	2x168.3	$0.5/(W/K)	1.30	22.8	1.02
Case 5	$2\text{x}8.657\text{x}10^4$	2x168.3	$1.0/(W/K)	1.30	45.5	1.02
ase 6	$2\text{x}8.657\text{x}10^4$	2x168.3	$2.0/(W/K)	1.30	91.05	1.02
ase 7	$10\text{x}8.657\text{x}10^4$	10x168.3	$0.5/(W/K)	1.30	4.56	1.02
ase 8	$10\text{x}8.657\text{x}10^4$	10x168.3	$1.0/(W/K)	1.30	9.11	1.0
Case 9	$10\text{x}8.657\text{x}10^4$	10x168.3	$2.0/(W/K)	1.30	18.2	1.02

Heat Exchangers Can Dominate The Costs, Even at Low Cost Levels and It is Extremely Difficult to Escape this Regime

- Considered 8 TE / Heat Exchanger Cost Conditions In the Cost Domain Map - $1.5/W to $2.9/W appears possible
  - Requires <$2/(W/K) - Aggressive Condition That May Require R&D Investment – Some Believe They Can Get this Now
- The $1-2/(W/K) Condition Still Does Not Escape the Heat Exchanger Cost-Dominated Regime

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